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Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) are non-invasive diagnostic imaging modalities that display internal anatomy of the middle and inner ear as two-dimensional cross-sectional slices. Radiologists and otolaryngologists can view these 2-D images and usually create a mental model of the 3-D structures present in the study. However, many of the tubular structures that exist in the temporal bone have complex morphology and pass back and forth through the cross sections. Endoscopists view organs from the inside, but a navigationally and spatially constrained, and, in the inner ear, real endoscopy is currently not possible. We demonstrate the use of 3-D computer graphics techniques to generate a non-invasive "virtual" otoscopy of the middle and inner ear from CT or MRI data, that avoids the difficulties of traditional techniques and permits views of the middle and inner ear not otherwise attainable. If developed, virtual otoscopy will permit planning the treatment of a variety of inner ear pathologies without the need for ablative labyrinthectomy.

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Introduction

Endoscopic approaches and minimally invasive techniques are now permitting visualization of previously inaccessible regions of the body using endoscopes which are fractions of millimeters in size. But there remain vital areas of the boy, within solid structures like the temporal bone, which can't be visualized at current levels of endoscopic sophistication.

Using the next generation of imaging and digital fusion capability, radiologists are developing tools to break through these endoscopic barriers. Some of the most promising recent accomplishments are in the area of three dimensional reconstruction, fusion and navigation through CT and MR data. Investigations in progress include those in neurosurgery (1), gastrointestinal surgery (2)(3) and endoscopic sinus surgery (4). A commercial product for arthroscopic procedures is even available (5). These capabilities are being used in pre-operative planning for unusual and difficult presentations, the development of innovative procedures as well as for the integration of new applications with advanced technologies.

Based upon these successes and sophisticated flight tracking programs from the military, virtual anatomical environments created with specific patient data can now be "flown" through and features "targeted" with nearly the realism available to modern fighter pilots.

There is the added advantage that with the virtual anatomy, point-of-view is not limited by physical boundaries. For example, bone and delicate membranes can be flown through non-invasively and perspectives achieved that are impossible even in open surgery. This approach was discovered separately and simultaneously by Lorensen (6) Geiger and Kikinis (7) and Vining (8). The following is the first report of this application to the fields of otologic and neuro-otologic surgery.

Body

Materials and Methods

The four main stages involved in the creation of a virtual otoscopic flythrough are slice acquisition, segmentation, generation of three-dimensional models, and flight path planning.

During slice acquisition, cross-sectional images are acquired using a CT or MR scanner and transferred via LAN to workstations in the lab. For this study, a formalin fixed specimen was positioned in a CT scanner (Siemens Somatom+, Erlangen, Germany) and 58 individual cross-sections were acquired with a field of view of 71 millimeters. Slice thickness and table feed from slice to slice were 1 millimeter. To minimize the appearance of slice artifacts in the final reconstruction, the slices were post-processed using a linear weighted maximum-likelihood interpolation technique to generate a new interpolated slice series of 180 slices with a smaller slice spacing of 0.?2 millimeters.

In the segmentation process, structures that we want to appear in the three dimensional reconstruction are identified and labeled, transforming the original gray-scale images into "labelmaps" so that the pixels belonging to each structure are identified by a unique number. In our lab, this process is performed using MrX (General Electric Medical Systems, Milwaukee, WI), a research program originally developed by General Electric's Corporate Research and Development Center in Schenectady and significantly expanded in our lab. MrX integrates a wide variety of image processing tools and algorithms to provide a computer-assisted segmentation environment. For larger structures that exhibit good contrast in the slice images, the segmentation process is almost completely automated; for the finer details, interactive editing and anatomical expertise are required.

For the 3-D visualization, we generated surface models, which allow visualization of the outer surface of solid objects, because the rendering of these models is efficient enough to permit animation-speed display using desktop hardware. The surface model is represented by a mesh of triangles that accurately approximate the shape of the object being modeled. An algorithm known as "Marching Cubes" (11)(12) produces the mesh for each of the structures labeled in the segmented slices. The resulting models often contain several hundred thousand triangles, so they are processed by a second algorithm, "Triangle Decimation," (9) which replaces adjacent triangles with single larger triangles where this is possible without altering the geometry of the model beyond a specified tolerance. This step is required to reduce the size and complexity of the final representation to a point where rendering speed is acceptable for animation.

We used a Sun SparcStation 20 (Sun Microsystems, Mountain View, CA) equipped with a ZX graphics accelerator (13) as the underlying hardware for the rendering and animation tasks. This configuration rendered our data (consisting of 148136 triangles) at an average speed of 1.8 frames per second during the flythrough. For stereo viewing, we utilized the stereo capabilities of the ZX board in conjunction with stereo glasses and a stereo controller (Crystal Eyes, Stereographics Corp., CA).

The generation and interactive display of the virtual otoscopy utilize programs written in LYMB, a high-level object-oriented language developed at GE. (10) LYMB incorporates a broad array of functionality with an emphasis on elements that facilitate scientific visualization, modeling and animation, particularly within the medical domain. The LYMB rendering module uses a "virtual camera" abstraction to facilitate intuitive specification of different views of the models. Using a "camera controller" interface, the user is afforded complete control of the position and focal point of the virtual camera within the model.

We employed a keyframing technique to generate the animation. In this process, the animator uses the camera controller to specify the views that should appear in the animation, in sequence. The computer records these views and provides smooth transitions between them by generating the intermediate frames. The resulting data file is a LYMB-parsable script, so the user can easily edit the animation and fine-tune it using the full versatility of the LYMB language. At this stage, we added text labels and made certain structures transparent for portions of the virtual otoscopy.

Results

We generated a 648 frame flythrough of the middle and inner ear using the procedures described in the previous section. The animation begins by approximating the view obtained during a conventional otoscopy, approaching the external auditory canal. However, in contrast to the real procedure, we choose to remove the skin (see figures 1 and 2). As a next step, however, the virtual camera passes through the eardrum and changes to 90 degree optics for an endoscopic view.

The space and maneuverability constraints of a conventional procedure are absent, of course, as is apparent when the virtual camera backs into a recess of the middle ear cavity for a clear view of the incus, malleus, stapes and stapedius muscle. The camera then flies along the middle ear cavity for a short distance until the cavity walls dissolve to reveal the inner ear structures. The view now includes the facial nerve, the geniculate ganglion, the greater petrosal foramen, the carotid artery, the internal auditory and the cochlea and semi-circular canals, all identified by different colors (see figures 3).

Now, outside the restrictive confines of the middle ear cavity, we revert to ordinary 30 degree optics to eliminate the distortion along the periphery caused by the wider-angle view (see figure 4-6). At this point text labels are inserted that identify the structures, and the virtual camera moves around and among the structures for a variety of close-up views. Finally, the camera backs away for a view from inside the skull where the entry-points of the carotid artery and facial nerve are visible. During the animation there is access to the original CT data. A marker can be set in either the CT data or the 3d renderings and will be visible on the other views.

This animation is fully interactive when displayed in the LYMB environment; the user can stop the animation at any point and use a variety of controls to manipulate the virtual camera or alter any of the attributes of a particular structure. The animation can then be resumed or restarted. Single frame stepping is also available. Finally, stereo viewing is possible using the stereo mode on the ZX accelerator, affording the viewer an even more realistic representation of the spatial configuration of the models.

Discussion

The virtual otoscopy demonstrates the application of interactive flythrough visualization techniques to a particularly difficult area of the anatomy, and reveals a tremendous potential in both clinical and educational settings.

This type of visualization has obvious applications in surgical planning, both pre-operatively and intra-operatively. While the virtual otoscopy is still in the research phase, our lab regularly uses 3-D reconstructions both for surgical planning and interactively during surgery, predominantly in the neurosurgical domain.

As an educational tool, flythrough visualizations provide dramatic improvements over textbook illustrations and photos, particularly when applied to complex anatomy like that of the middle and inner ear. The flythrough provides 3-D cues that are not otherwise present so that the location and anatomical relationships of structures in a region as complex as the ear are more easily grasped. The addition of text labels further enhances the educational value of this type of display.

Once the models and animations are produced, using LYMB, it is possible to generate an MPEG ``movie" from the flythrough which is not interactive, but captures the essential characteristics of flythrough visualization. This alternative format can be displayed on virtually any personal computer, which could make widespread educational application both practical and economical. The MPEG format permits surgeons to further study cases on their own personal computer, without having to utilize special equipment which may be less convenient or accessible.

Further improvements in virtual reality techniques and stereoscopic visualization tools will likely enhance this new image representation method. A split screen could display the endoscopic view simultaneously with a view from an outside perspective and a display of the nearest cross-sectional slice. Two-dimensional and 3-D markers could track the position of the virtual endoscope, and provide a cross-referencing capability between the views. In the future, advanced virtual reality interface devices may further enhance the process of exploration and interactive navigation within the models.

Conclusion

Virtual otoscopy is clearly in its formative stages but portends a potential beyond our current grasp. Segmentation processes and pathological distinctions are not yet sophisticated enough to generate high resolution images comparable to optical endoscopy and which enable the sometimes subtle distinctions indicative of disease. Therapeutic procedures cannot be performed but "routine screening" may soon be cost-consciously possible. In this sense, the new capabilities will be more an adjunct than a replacement. For examination of the middle ear and structures within the temporal bone, an entirely new dimension of care will be provided. The challenge is perhaps not so much that of virtual otoscopy replacing standard procedures but rather who will be performing it.

Acknowledgment
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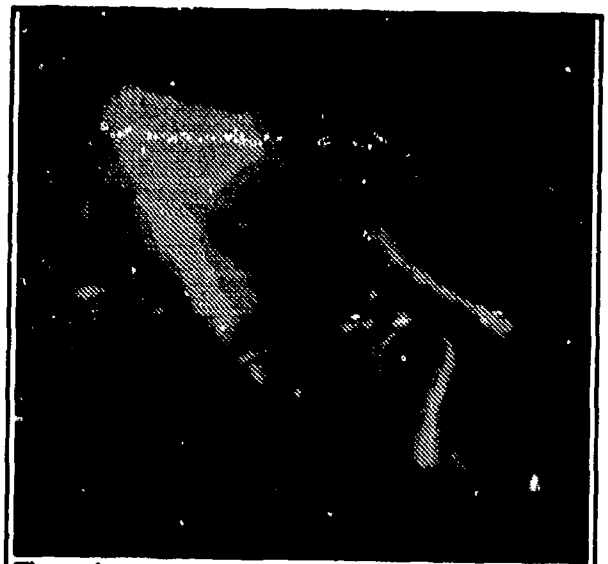

Figure 1

Figure 1:
Lateral view of the temporal bone. The external auditory canal, the mastoid and the temporo andibular joint are visible. The eardrum is visible at the bottom of the external auditory canal.

Figure 2

Figure 2:
The virtual otoscopic camera is now inside the external auditory canal. The handle of the malleus is visible through the orange eardrum.

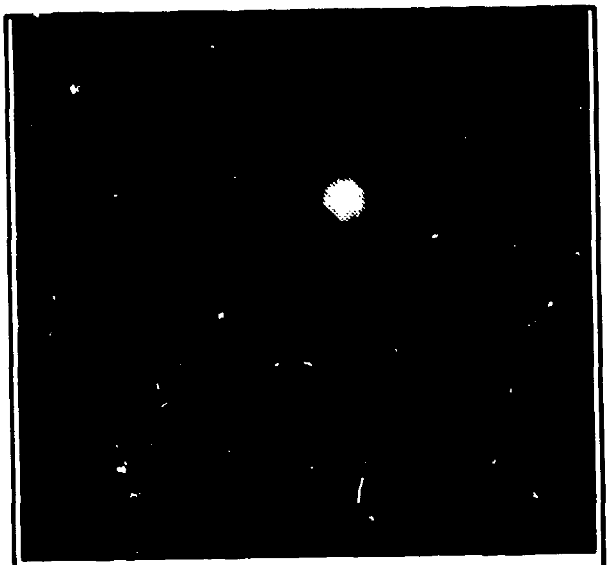

Figure 3

Figure 3-6:
View of the soft tissues of the petrosal bone: The facial nerve is colorized yellow, the cochlea and the semicircular canals are colorized blue. The geniculate ganglion is represented in a tan color and the greater petrosal foramen is colorized in a darker brownish hue. The carotid is colorized in red and internal auditory canal and its branches is colorized in an orange color. Of the bones of the middle ear, incus and stapes are colored green, the malleus is colored in a flesh tone.

Figure 3: A close up view of the geniculate ganglion. A white spheric marker is positioned in the ganglion.

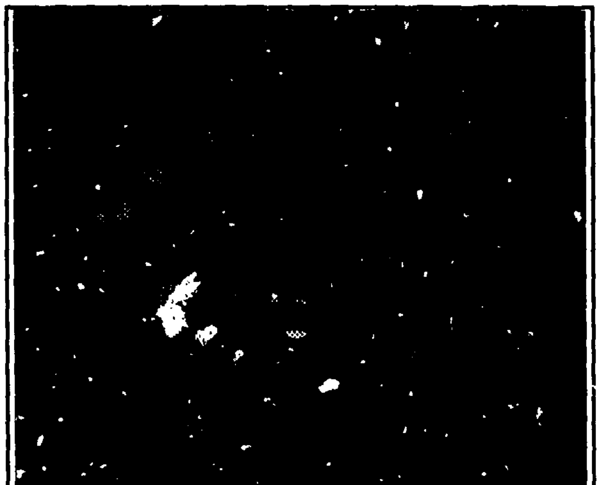
Figure 4

Figure 4: A view from farther away. The virtual camera that was used to take figure 3 is represented as a yellow box with a blue pyramid marking the upside.

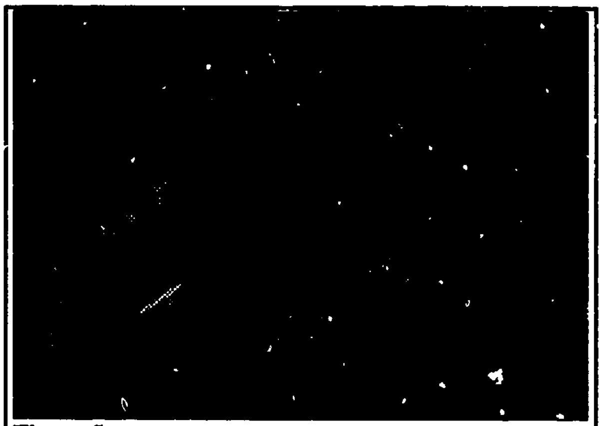

Figure 5

Figure 5: On this view the geniculate ganglion and the greater petrosal foramen have been removed, partially exposing the cochela.

Figure 6

Figure 6: The internal auditory has also been removed to further expose the cochlea.

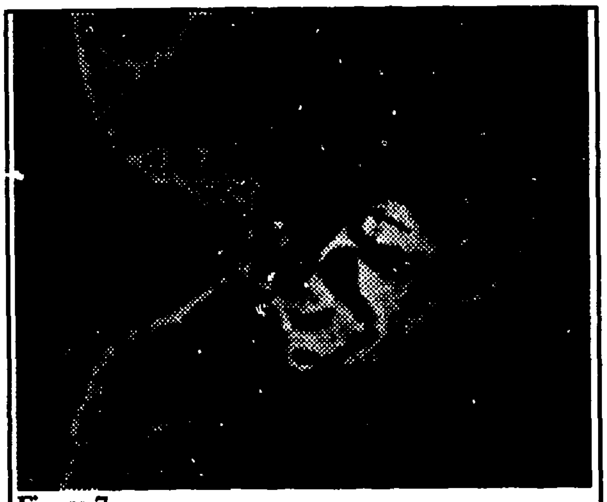

Figure 7

Figure 7: Corresponding CT slice. This is the data from which the 3d models were generated. The black arrow points at the geniculate ganglion.

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